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Mechanical properties of green structural concrete with ultrahigh-volume fly ash

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HIGHLIGHTS

- With a FA/binder of 80%, Grade 45 green concrete for structural use is developed.
- Adequate workability is maintained in green concrete for normal construction.
- Adding a small amount of SF can improve both mechanical and sorptivity performance.
- FA replacement level (FA/b ≤80%) has no obvious effect on FA cementing efficiency.
- Green concrete shows obvious superiority in environmental impact and material cost.

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ABSTRACT

Using a high dosage of fly ash in concrete is an effective approach to control the heat release rate, reduce the material cost and enhance the sustainability. However, ultrahigh-volume fly ash (UHVFA) concrete, with fly ash replacing over 60% of the binder by weight, often exhibits low compressive strength at an early stage, which limits the material to non-structural or semi-structural applications. Though different approaches have been proposed to increase the strength, the efficacy of some of the methods is debatable, because of the high energy consumption and/or low cost-benefit ratio. This study aims to increase the compressive strength of UHVFA concrete by the simple and practical method of reducing the water/binder ratio while adding super-plasticizers to maintain workability. Mortar samples were used to explore the influence of silica fume, and Portland cement was replaced with fly ash at five different percentages (20%, 40%, 60%, 80% and 98%). Mechanical properties up to 360-day age were recorded, and the cementing efficiency factor of the fly ash was studied. With a suitable mix proportion, even with 80% of the binder replaced by fly ash, the compressive strength of the mortar and concrete can reach over 40 MPa at 7-day age, and over 60 MPa at 28-day age. Compared to commercial Grade 45 concrete, the proposed green structural concrete shows a reduction in CO_2 emission of around 70%, a reduction in embodied energy of more than 60%, and a reduction in material cost of 15%.

1. Introduction

Fly ash (FA), or pulverized fuel ash (PFA), is a principal by-product of coal combustion in thermal power plants. These few years, around 600 million tonnes (MT) in China, around 220 MT in India and around 130 MT in the U.S. of fly ash is generated, and only approximately 70%, 60% and 50% of the fly ash is reused, respectively [1,2]. The large amount of remaining fly ash is disposed in landfills with the potential risks of air pollution and contamination of water due to leaching [3–5], not to mention that landfill space is becoming scarce in many urban neighborhoods. On the other hand, cement production is a highly energy intensive process that generates large amounts of CO_2, SO_2 and NO_x [6,7]. Since the early 1960s, many countries have started to incorporate fly ash into concrete as a pozzolanic material that may be used either as a component of blended Portland cement or as a mineral admixture in concrete. Substituting cement with fly ash in the mixture design of concrete brings a number of benefits. Firstly, replacement of cement by fly ash increases the environmental greenness and decreases the hydration heat as well as the material

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cost. Secondly, the addition of fly ash can enhance durability [8] and reduce drying shrinkage [5]. Thirdly, the morphological and micro-aggregate effects of un-hydrated fly ash particles with small particle size and smooth spherical shape, result in better workability, higher compactness in the interfacial transition zone and a finer pore structure in the system [9–12].

Concrete with fly ash replacing 15–30% (hereafter, by weight) of the binder has been widely used, and researchers and engineers have developed the high-volume fly ash (HVFA) concrete, with 30–60% of fly ash in the binder. Desirable mechanical and durability properties of HVFA concrete has been achieved by careful selection of the mix proportions and the utilization of super-plasticizers [13]. Hence, there is wide interest in further increasing the replacement percentage of fly ash. This study focuses on ultrahigh-volume fly ash (UHVFA) concrete, defined here as the concrete with fly ash replacing more than 60% of the binder.

From the chemical viewpoint, in fly ash-cement systems, the highly amorphous silica and alumina phases in Class F fly ash react with the Portlandite to form additional calcium-silicate-hydrate (C-S-H) and/or calcium-aluminate-silicate-hydrate (C-A-S-H) phases [14–17], the so-called pozzolanic reaction. As the pozzolanic reaction of fly ash is a relatively slow process, its contribution to concrete strength occurs mainly at later ages, so the early strength (normally up to 28 days) would be significantly reduced if a large amount of fly ash is used [18,19]. The table in the Supplementary material summarizes the compressive strength of UHVFA concrete, with normal curing conditions and without chemical activation. Each column in the table gives the study reference, the mix composition, the strength at 28 days as well as the strength at other ages (with the curing days given in brackets). The results are mostly obtained for Class F fly ash, and those for Class C fly ash are explicitly stated in the first column. It should be noted that different studies utilized different specimen geometries for compressive testing, and the data was converted to the apparent strength of the cube specimen measuring 100 mm × 100 mm × 100 mm, based on the corresponding correction factor [20,21]. Fig. 1 illustrates the 28-day compressive strength versus the water/binder ratio, based on the data given in the Supplementary material. The figure indicates that only a small fraction of the mixes (9 out of 57) can reach compressive strength of over 40 MPa, and only 3 sets of data show compressive strength beyond 50 MPa at the 28-day age. This obviously limits the structural applications of UHVFA concrete. Researchers have explored different approaches for improving the situation, including: (i) lowering the water/binder ratio [14], (ii) substitution of a high-early strength Portland cement for ordinary Portland cement [22], (iii) replacement of a portion of the fly ash with a more reactive pozzolan such as silica fume or rice husk ash [22], (iv) chemical activation [23–25] (v) incorporating nano-materials (such as nano-SiO_2) [8], (vi) accelerated curing and autoclaving [26,27], and (vii) mechanical treatment (grinding) [28,29]. However, the efficacy of some of these methods is debatable because of the high energy consumption (Methods VI and VII) and/or the low cost-benefit ratio (Methods IV to VII). Hence, the first three methods may be more practical in general.

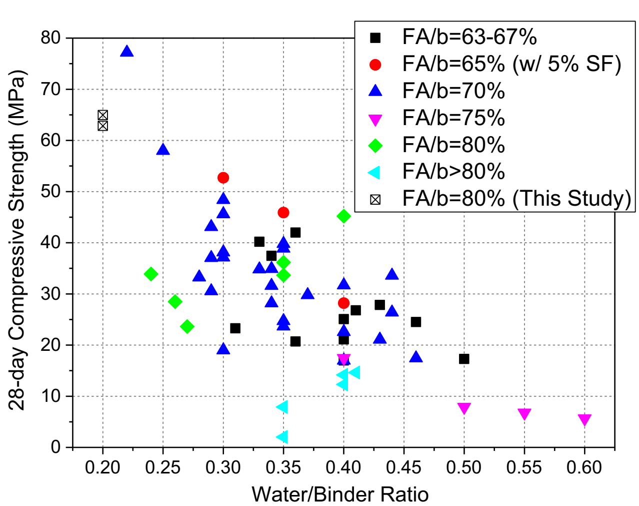

Fig. 1. 28-Day compressive strength vs water/binder ratio of UHVFA concrete.

2. Research objective and significance

This study aims to improve the compressive strength of ultrahigh-volume fly ash (UHVFA) concrete with a practical approach. Since UHVFA incorporation might lead to low early strength, a target of 40 MPa for 7-day-old concrete was set to avoid delays in the construction process due to insufficient strength gain, and a target of 55 MPa for 28-day-old concrete was set for attaining comparable strength to Grade 45 structural concrete. According to the data summarized in Fig. 1, 28-day compressive strength of over 50 MPa was reported in studies with no more than 70% of Portland cement replaced by fly ash. However, previous work of the authors on fiber reinforced pseudo-ductile cementitious composites (with very high binder ratio and only a small amount of sand in the mix) demonstrated that such strength is achievable even if 80% of the binder is replaced by fly ash, in conjunction with a low water/binder ratio and a very small amount of silica fume [30,31]. Hence, the target weight replacement fraction of the fly ash in the binder was set as 80%, and the water/binder ratio was kept as 0.20. Mortar samples were first employed to explore the effect of binder composition, where Portland cement was replaced with fly ash at five different percentages (20%, 40%, 60%, 80% and 98%). Mechanical properties up to 360-day age were recorded, and the cementing efficiency factor of fly ash was studied. Based on the findings, a green concrete with very high fly ash content was developed and compared to commercial Grade 45 concrete in terms of strength, cost as well as environmental impact. This research extends the use of UHVFA concrete in civil engineering applications, and widely promotes the concept of sustainability to the community. For countries like China and India, this technology can play an important role in meeting the huge infrastructure demands in a sustainable manner [22].

3. Experimental program

3.1. Materials, mixing and curing

The materials used in this study included cement, fly ash (FA), silica fume (SF), river sand, granite gravel and super-plasticizers. Type One 52.5 N Portland cement was manufactured by Green Island Cement Co., Ltd in Hong Kong, and met all the requirements of BS EN 197-1 [32]. Both Class F and Class C fly ash were provided by China Power and Light Co., Ltd in Hong Kong, and their SEM images are shown in Fig. 2. The silica fume was Microsilica 920U, provided by Elkem Co., Ltd in Norway. Table 1 lists the chemical compositions of the cement, fly ash and silica fume, while Fig. 3 presents their particle size distributions. The maximum size of the granite gravel was 20 mm. To ensure sufficient workability of the mix with a low water/binder ratio, the ADVA 105 polycarboxylate-based super-plasticizers, provided by Grace Construction Products in Hong Kong, was utilized to adjust the rheological properties of the mixes.

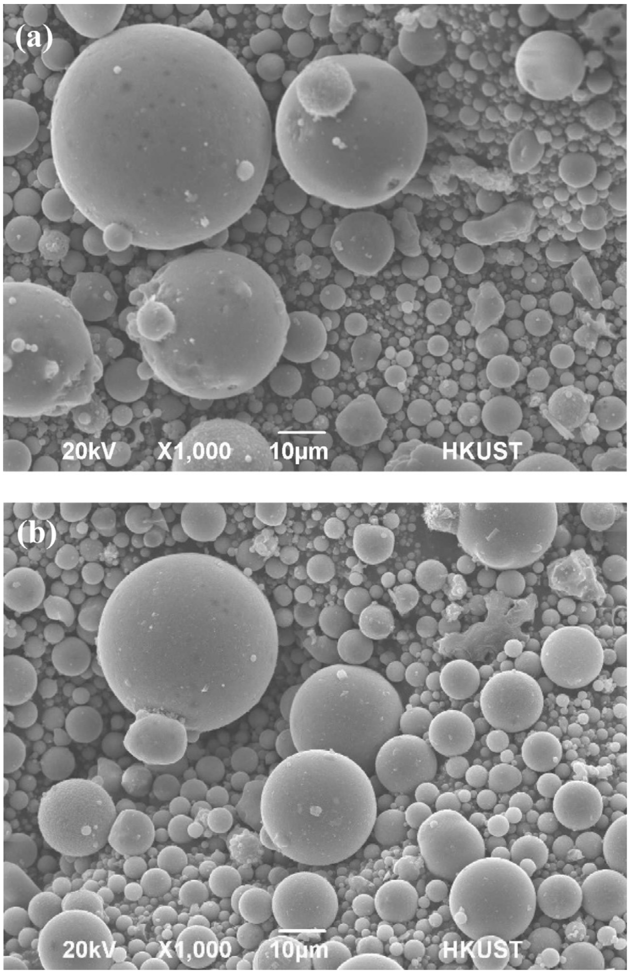

Fig. 2. SEM images of fly ash.

The experimental study was performed in two steps: (i) determining the appropriate mix composition of UHVFA mortar to provide sufficient strength, and (ii) designing a Grade 45 Green Concrete with such a composition. In the experimental program, the authors first fixed the FA/binder ratio as 80% to study the effect of silica fume and sand content in the mortar. The Mortar-SF series (only Class C fly ash was employed) in Table 2 was prepared for the determination of strength at the early stage (1-day, 3-day, 7-day and 28-day ages). In this series, SF/binder ratios of 0%, 2% and 4% were employed, to determine if a small amount of silica fume can facilitate the strength development when the fly ash content is very high. Once the proper content of silica fume was obtained from the first test series, the Mortar-S series with varying sand content was tested, to obtain the optimal sand content for UHVFA mortar. The influence of FA/binder ratio (from 20% to almost 100% by weight) was also explored in the Mortar-FA series. The Mortar-Normal series was designed for the comparison. Finally, with the proper mortar composition, green UHVFA concrete was prepared (Table 2), together with two local commercial concrete mixes denoted as C45 and C42FA for comparison. For the Mortar-S, Mortar-FA and Concrete series, samples were tested at 7-day, 28-day, 90-day and 360-day age. It should be noted that the dosage of super-plasticizers in Table 2 was the amount in solution form (with 30% solid content). To achieve similar workability, different amounts of super-plasticizers might be required for different types of fly ash, as discussed in literature [31,33].

A Hobart™ HL800 mixer was used to prepare the mortars, while an ordinary pan concrete mixer was utilized to mix the concrete. The normal slump test [34] was performed to determine the workability of the green concrete mixes. All the specimens were cast in greased steel molds on a vibrating table. After finishing the surface, the specimens were covered with polyethylene sheets to prevent loss of moisture. It has been reported that Class F fly ash, especially with high loss on ignition (LOI), increases the setting time, while Class C fly ash sometimes exhibits the opposite behavior of reducing the setting time [35,36]. In the present study, the specimens were stored for either 24 hours (for the Mortar-Normal series and Mortar-SF series in Table 2, in order to measure the 1-day strength) or 48 hours (for the other series in Table 2) at room temperature prior to demolding. After demolding, the samples were cured in a fog room at a temperature of 23 ± 2 °C and relative humidity of 95 ± 5%, until testing.

3.2. Specimens and testing procedures

For each mortar mix in Table 2, three prismatic specimens of dimensions 160 mm (length) × 40 mm (width) × 40 mm (height) were utilized for three-point bending with a supporting span of 100 mm, and the six broken half prismatic specimens from the bending tests were used for compression tests [37]. Compressive testing was performed with a standard sample holder to ensure a 40 mm × 40 mm loading area, with the test procedure following BS EN 1015-11:1999 [37]. For concrete, the prismatic specimens were 300 mm (length) × 75 mm (width) × 75 mm (height) in size and the supporting span was 180 mm. Following similar test procedures to those mentioned above, two steel plates of size 100 mm (length) × 75 mm (width) × 10 mm (thickness) were placed on the top and the bottom of the half prisms to ensure a 75 mm × 75 mm loading area for compression. It should be noted that the test result was converted to the apparent strength of the cube specimen measuring 100 mm × 100 mm × 100 mm, based on the corresponding correction factor [20]. A servo-hydraulic MTS 810 testing system was used in the displacement control mode to conduct the three-point bending tests at a loading rate of 0.05 mm/minutes. An automatic compression testing machine was utilized to perform the compression tests for mortar and

Table 1
Chemical compositions of cement, fly ash and silica fume.

Materials	LOI[a] (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Na_2O (%)	K_2O (%)	Active SiO_2[b]
Portland Cement	1.17	20.15	4.38	3.37	63.85	2.13	4.66	0.11	0.38	–
Fly Ash (Class F)	2.49	49.83	18.94	11.43	9.27	3.57	2.13	1.55	1.80	70%
Fly Ash (Class C)	1.26	38.29	15.49	14.44	18.47	7.76	2.49	0.03	1.38	75%
Silica Fume	1.03	93.43	0.69	1.07	0.42	1.21	0.41	0.95	1.17	98%

[a] LOI: Loss on ignition.
[b] The fraction of SiO_2 that is soluble after treatment with hydrochloric acid (HCl) and with boiling potassium hydroxide (KOH) solution (BS EN 197-1 [32]).

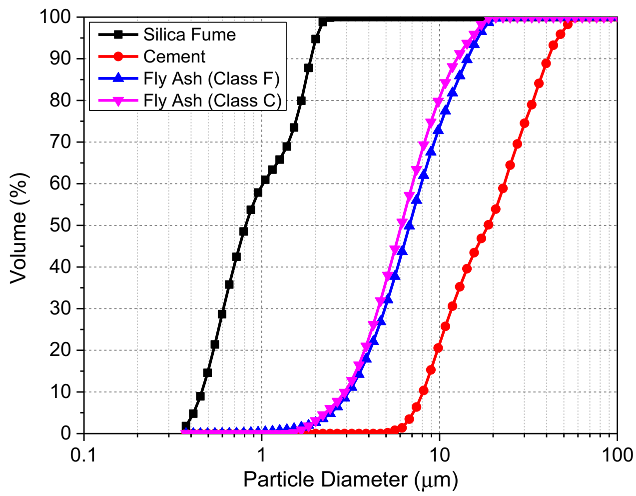

Fig. 3. Particle size distribution of cement, fly ash and silica fume.

concrete, with a loading rate of 0.3 MPa/s. The sorptivity test of the Mortar-SF series (Table 2) was based on ASTM C 1585 [36], with a cubic specimen measuring 50 mm × 50 mm × 50 mm.

4. Test results and discussion

4.1. Influence of silica fume

4.1.1. Mechanical performance of Mortar-SF series

Fig. 4a–b present the development of flexural and compressive strength with age of the Mortar-SF series. The data of two normal mortar mixes (M45 and M42FA as listed in Table 2) are also shown in the figure for comparison. To make the figures clearer, only half of the standard deviation bars are shown. The flexural strengths of the three UHVFA mixes are quite similar to each other, and show significant improvement with increasing curing time. For normal mortar, the flexural strength reaches about 5 MPa at 1-day age,

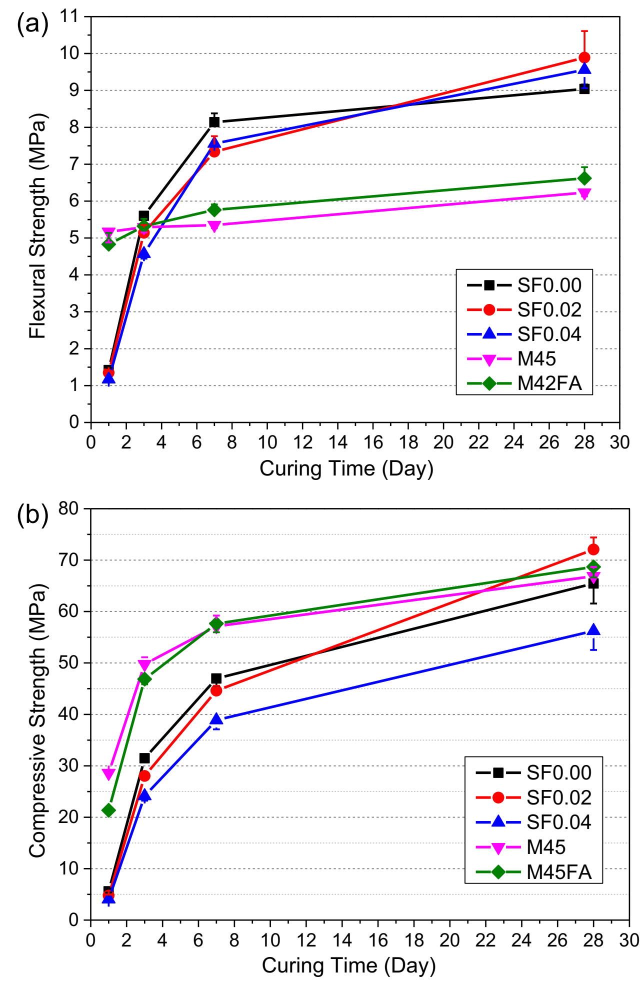

Fig. 4. Mechanical properties of Mortar-SF series.

Table 2
Mix proportion (by weight).

Series	Mix ID	Binder			Sand/Binder	Gravel/Binder	Water/Binder	SP/Binder (%)	
		Cement	Fly Ash	Silica Fume				Class F	Class C
Mortar-Normal	M35	1.00	0	0	2.0	0	0.35	0.40	
	M42FA	0.75	0.25	0	2.0	0	0.42	NA	0.36
	M45	1.00	0	0	2.0	0	0.45	0.00	
	M55	1.00	0	0	2.0	0	0.55	0.00	
	M72	1.00	0	0	2.0	0	0.72	0.00	
Mortar-SF	SF0.00	0.20	0.80	0.00	2.0	0	0.20	NA	1.27
	SF0.02	0.18	0.80	0.02	2.0	0	0.20	NA	1.29
	SF0.04	0.16	0.80	0.04	2.0	0	0.20	NA	1.76
Mortar-S	S1.0	0.18	0.80	0.02	1.0	0	0.20	0.82	0.69
	S1.5	0.18	0.80	0.02	1.5	0	0.20	0.97	0.86
	S2.0	0.18	0.80	0.02	2.0	0	0.20	1.39	1.29
	S2.5	0.18	0.80	0.02	2.5	0	0.20	3.27	3.23
Mortar-FA	FA20	0.78	0.20	0.02	2.0	0	0.20	1.99	1.92
	FA40	0.58	0.40	0.02	2.0	0	0.20	1.76	1.68
	FA60	0.38	0.60	0.02	2.0	0	0.20	1.53	1.44
	FA80	0.18	0.80	0.02	2.0	0	0.20	1.39	1.29
	FA98	0	0.98	0.02	2.0	0	0.20	1.28	1.21
Concrete	Green	0.18	0.80	0.02	1.2	2.4	0.20	1.45	1.39
	C45	1.0	0	0	1.2	2.4	0.45	0.00	
	C42FA	0.75	0.25	0	1.64	2.16	0.42	NA	0.35

Note: SP: Super-plasticizers; NA: Not available.

but the further increase is limited with increased age. After 3 days, the flexural strength of UHVFA mortar is higher than that of normal mortar. As for the compressive strength, both SF0.00 and SF0.02 reach around 5 MPa at 1-day age, around 30 MPa at 3-day age, around 45 MPa at 7-day age and over 65 MPa at 28-day age. At 28-days, the compressive strength of the UHVFA mortars is comparable to that of normal mortars. The poor performance of SF0.04 is likely a result of the poor workability caused by the high content of very fine powder (silica fume here), especially when the water content is also low in the mix. In addition, further addition of superplasticizers has no significant effect on the workability of SF0.04.

In the present study, a very small amount (less than 5% of the total binder content) of silica fume was used to replace Type One 52.5N Portland cement. No big differences were observed in early strength (up to 7-day age) between SF0.00 and SF0.02, and previous studies reported and discussed similar phenomena in concrete with a normal content of fly ash replacement [21,38].

4.1.2. Sorptivity of Mortar-SF series

The movement of water into cementitious materials was fully modelled by Hall [39] using a square-root-time relationship. The absorption is determined by the change in mass divided by the product of the cross-sectional area of the test specimen and the density of water. By using least-squares linear regression analysis, as in Fig. 5, the initial rate of water absorption Si (mm/$s^{1/2}$) is defined as the slope of the line that is the best fit to the absorption plotted against the square root of time ($s^{1/2}$) using the points from 1 min to 6 h, while the secondary rate of water absorption Ss (mm/$s^{1/2}$) is defined as the slope using the points from 1 d to 7 d [40].

Table 3 lists the rate of water absorption of the Mortar-SF series. The data of two normal mortar mixes (M45 and M42FA as listed in Table 2) are also shown in the figure for comparison. Compared with normal mortar and concrete, the lower initial rate of water absorption of SF0.00 may be attributed to a significantly lower water-to-binder ratio, while the higher secondary rate of water absorption results from the high fly ash content. The present result shows that adding 2% of silica fume can significantly reduce the water sorptivity, which makes SF0.02 perform better than both SF0.00 and M42FA. The poor performance of SF0.04 likely results from the poor workability and the increased number of pores, as discussed in Section 4.1.1. In addition, it has also been reported that introducing a small amount of silica fume can improve the durability by modifying the interfacial transition zone as well as reducing the chloride permeability and porosity of HVFA concretes [9,38,41–44]. Based on these considerations, the SF/binder ratio was set as 0.02 for later study.

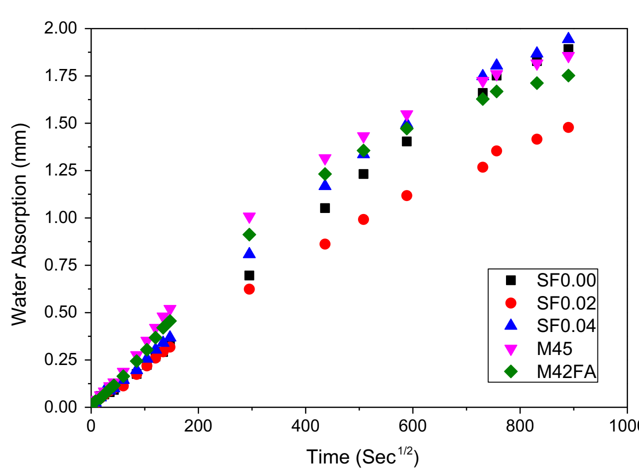

Fig. 5. Water absorption of Mortar-SF series.

Table 3
Sorptivity of Mortar-SF series.

Mixture	Initial absorption rate *Si* (10^{-4} mm/$s^{1/2}$)	Secondary absorption rate *Ss* (10^{-4} mm/$s^{1/2}$)
SF0.00	21.3	22.2
SF0.02	20.9	15.2
SF0.04	24.4	21.1
M45	35.2	15.7
M42FA	31.2	15.7
Normal concrete with w/c of 0.4 [21]	116	–
OPC concrete with w/c of 0.4–0.5 [52–54]	297	–

4.2. Influence of sand content on mechanical properties of Mortar

Fig. 6a–b summarize the effect of sand/binder ratio (from 1.0 to 2.5) on mortar strength, for both Class F and Class C fly ash. In general, the same mix with Class C fly ash shows higher strength than that with Class F fly ash, and S2.0 (with sand/binder ratio of 2.0) has the best performance among all the mixes. Hence, based on the present materials and results, the authors recommend a sand/binder ratio of 2.0 for UHVFA mortar in practice, which lies at the lower end of the values for normal mortar [21].

The poor workability of S2.5 with Class F fly ash resulted in relatively poor mechanical strength (Fig. 6a), as there is likely

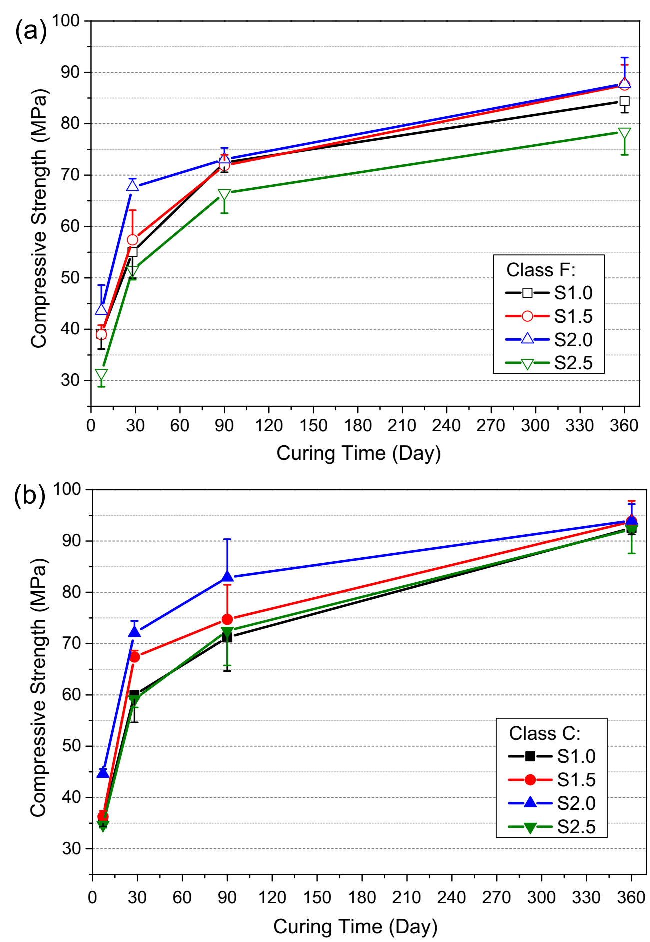

Fig. 6. Compressive strength development of Mortar-S series.

insufficient water for lubrication in this mix, due to the high sand content and low water/binder ratio. Further addition of super-plasticizers has no significant effect on the workability of S2.5 with Class F fly ash, and may be due to the high loss on ignition (LOI) content of Class F fly ash in this study (Table 1). In particular, the unburned carbon particles in fly ash, which are usually the most important contributor to the LOI, can significantly affect the fresh properties of the concrete. While the carbon particles do not take part in the hydration reaction, they do affect the water demand for the standard consistency stage. In addition, carbon particles have a strong affinity toward organic chemical admixtures, and will influence the effectiveness of super-plasticizers [31,33], especially for the current case with a low water/binder ratio.

4.3. Influence of fly ash

4.3.1. Mechanical performance of Mortar-FA series

The Mortar-FA series studies the variation of mechanical properties with different fly ash content, with the SF/binder ratio fixed at 0.02 and the sand/binder ratio equal to 2.0. Case FA80 is hence the same as SF0.02 in the Mortar-SF series and S2.0 in the Mortar-S series. The result in Fig. 7 shows the strength development of the Mortar-FA series. When the FA/binder ratio is no more than 60%, the extremely low water/binder ratio results in very high strength, and the difference between the mix with Class C or Class F fly ash is not apparent. For FA80, the mix with Class C fly ash shows a slightly higher value than that with Class F fly ash, and both mixes achieve the target compressive strength, which is more than 40 MPa at 7-day age and more than 55 MPa at 28-day age. For FA98, the rate of strength development of the Class C fly ash mix was higher compared to the Class F fly ash mix. As Class C fly ash has much higher calcium content than Class F fly ash, it can generate C-S-H through the hydration reaction of the calcium oxide and silicates it contains, in addition to that produced from the pozzolanic reaction with $Ca(OH)_2$ in the hydration products of Portland cement. Generally, Class C fly ash reacts earlier than Class F fly ash, but some Class C fly ash does not contribute a long-term increase in strength [45]. In the present case, however, the mix with Class C fly ash still shows remarkable strength improvement after one year.

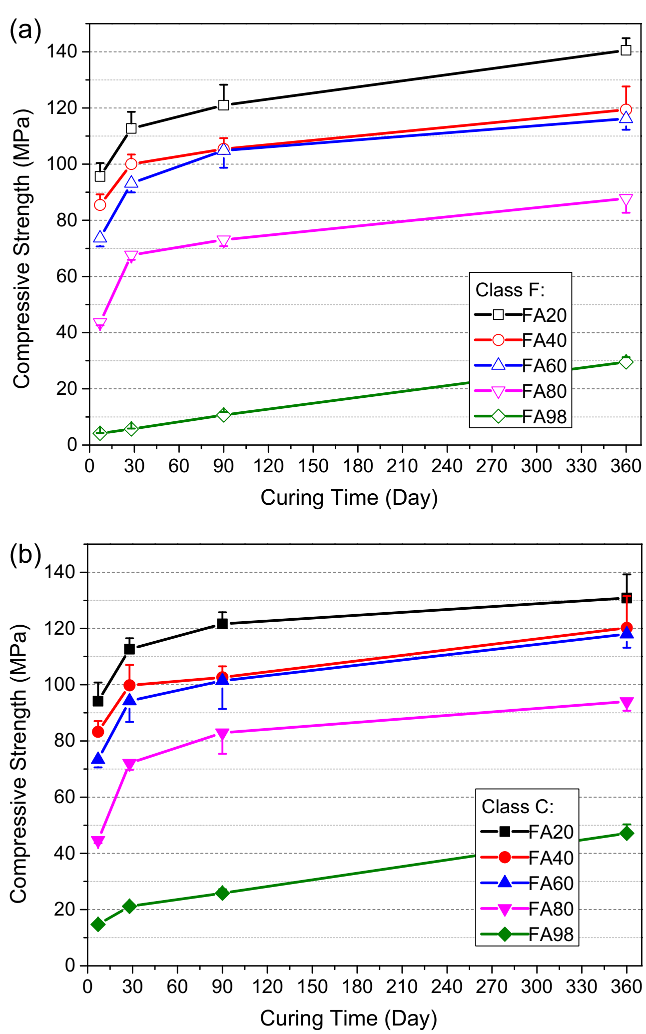

Fig. 7. Compressive strength development of Mortar-FA series.

4.3.2. Cementing efficiency of fly ash

A reliable prediction of concrete or mortar strength based on the contribution of each component is very difficult. The contribution of cement replacement materials (CRM) to strength is often expressed in terms of a cementing efficiency factor (k), which is a measure of the relative contribution of the CRM to the strength, compared to an equivalent weight of ordinary Portland cement [46].

For 28-day-old mortars in the present study, the cementing efficiency factor of silica fume, Class F fly ash and Class C fly ash are assumed to be $k_{sf} = 3$ [47], $k_{fa} = 0.3$ [46] and $k_{fa} = 0.35$, respectively. The value of the equivalent water/cement ratio can then be obtained as $W/(C + k_{sf} \times SF + k_{fa} \times FA)$, where W is water content, C is Portland cement content, SF is silica fume content and FA is fly ash content. With the data from the Mortar-Normal Series and Mortar-FA Series in Table 2, and the figure on compressive strength versus water/binder ratio of concrete in BRE [48], the comparison is shown in Fig. 8. The figure from BRE [48] is extended with the horizontal axis to 0.2, and the vertical axis up to 120 MPa. It can be seen that if the FA/binder ratio is no more than 80%, the fly ash replacement ratio has no obvious effect on the cementing efficiency of fly ash, since the data points follow the trend line. However, when the fly ash content is further increased, the cementing efficiency of the fly ash decreases significantly, which may be due to the lack of $Ca(OH)_2$ for the pozzolanic reaction. Of course, the cementing efficiency factor also depends on curing conditions, as well as the curing time.

4.4. Green structural concrete

Based on the results from the mortar samples, the authors propose green concrete with composition given in Table 2, and measured both the fresh and hardened properties.

4.4.1. Fresh properties

Fig. 9 shows a typical slump test result on fresh green concrete. With the use of Class F or Class C fly ash, the slump values range from 180 to 200 mm and the spread diameter varies from 400 to 450 mm. This is classified as S4 in BS EN206 [49] and is suitable for general construction. Moreover, the mix has remarkable thixotropy. Following the commonly used Bingham or modified Bingham rheological model [21] for concrete, the mix has relatively high shear yield stress and low plastic viscosity. This kind of concrete has good compactability, cohesiveness and shape stability, and shows excellent fluidity under vibration.

4.4.2. Mechanical performance

Fig. 10a–b illustrate the mechanical test results on green concrete made with Class C or Class F fly ash, together with two

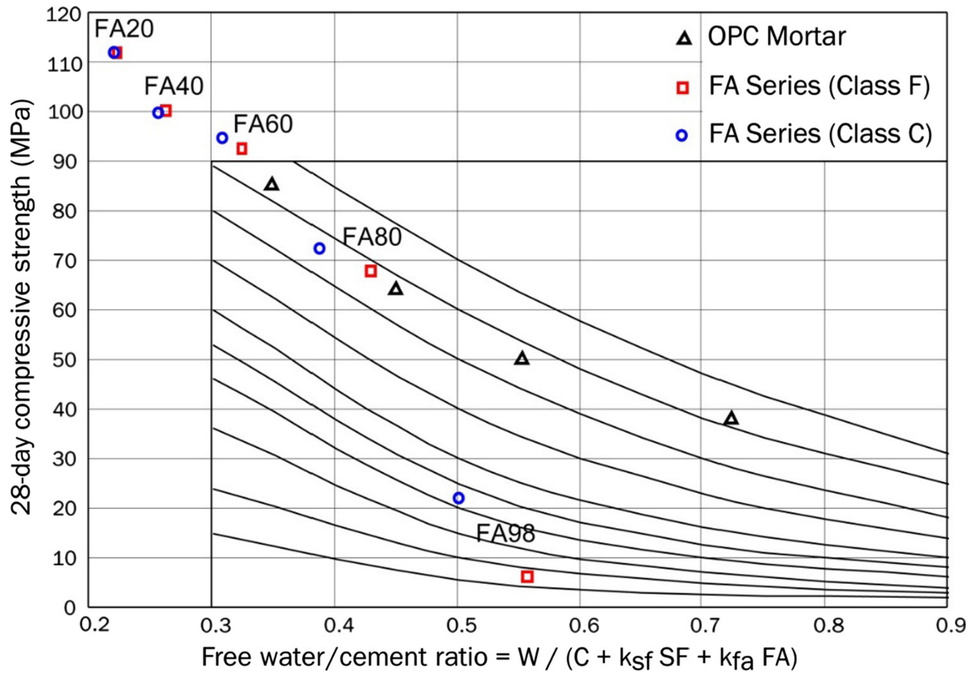

Fig. 8. Compressive strength vs free water/cement ratio of concrete.

Fig. 9. Slump test of fresh green concrete.

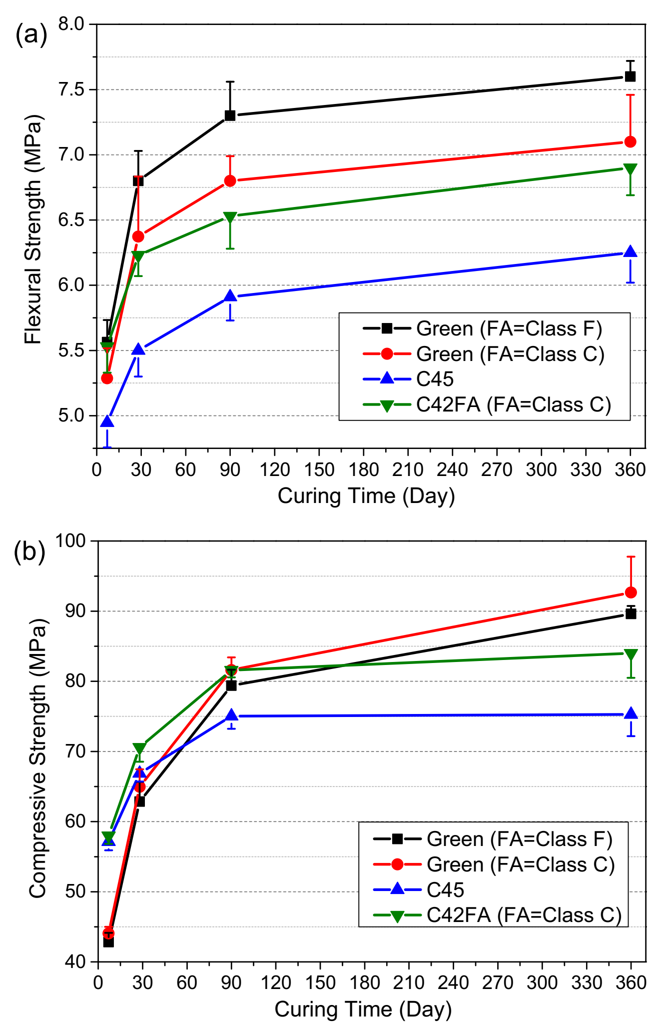

Fig. 10. Mechanical properties of Concrete series.

commercial Grade 45 concrete with no fly ash (C45) and 25% fly ash replacement (C42FA). The development of flexural strength with curing age shows a normal increasing trend for all mixes. The flexural strength of green concrete reaches comparable value to conventional concrete from 7-day age onwards. At 28-day age, the compressive strength of green concrete is slightly below that of conventional concrete. However, the green concrete with Class F fly ash and Class C fly ash can both achieve the target compressive strength of over 40 MPa at 7-day age and over 55 MPa at 28-day age, and these results are also presented in Fig. 1 for a clear comparison to the data from the literature. At 90 days, the compressive strength of the green concrete has exceeded that of C45 and is getting very close to C42FA. Also, the rate of further strength development appears to be higher for the green concrete than the

Table 4
Energy intensity, CO_2 emission and material cost for each component of concrete.

Material	Energy intensity (MJ/kg)	CO_2 Emission (kg/tonne)	Cost (HKD/tonne)
Portland Cement	5.5 [55]	930 [55]	800
Fly Ash	0.1 [55]	8 [55]	200
Silica Fume	0.1 (Assumed)	8 (Assumed)	3000
Sand	0.081 [55]	4.8 [55]	140
Granite Gravel	0.083 [55]	4.8 [55]	110
Water	0.01 [55]	1 [55]	7
Polycarboxylate-Based Super-Plasticizers	11.47 [56]	600 [56]	10,000

Table 5
Material sustainability indicators and cost comparison of different concrete mixtures.

Mixture	Embodied Energy (MJ/m^3)	CO_2 Emission (kg/m^3)	Cost (HKD/m^3)
C45	2757	450	587
C42FA	2072	331	531
Green Concrete	765	100	468

conventional concrete mixes, which is the result of the pozzolanic reaction of fly ash.

5. Environmental impact and cost comparison

To quantify the environmental impact, the authors used the Material Sustainability Indicators (MSIs). MSIs are calculated based on energy and material flow in the manufacturing process, and are expressed in terms of energy consumption, waste, and pollutant release [10,50]. The present study adopts two major MSIs, embodied energy and embodied carbon content (expressed as CO_2).

Table 4 lists the energy intensity, CO_2 emission and material cost (based on data in Hong Kong) for each component of concrete. The authors assume the energy intensity and CO_2 emission value of silica fume is the same as that of fly ash. The MSIs per unit volume of conventional concrete C45 and C42FA, and green concrete (with Class C fly ash) in the current study, are calculated and summarized in Table 5. For both the energy intensity and CO_2 emission, the MSI of green concrete is around 1/4 to 1/3 that of conventional concrete. At the same time, the material cost of green concrete shows a decrease of around 15% relative to normal concrete currently in use. It should be noted that the MSIs and cost comparisons in the present study only focus on the manufacturing process of the material used. True assessment of the total environmental impact and cost should be evaluated based on the life-cycle analysis of a specific type of structure [50,51], which would also require data on the material durability.

6. Conclusions

In this study, the mechanical properties of green structural concrete with ultrahigh-volume fly ash (UHVFA) were experimentally explored. While the properties of UHVFA concrete may be affected by the chemical composition and physical properties of fly ash, based on the materials and test results of the present study, the following conclusions can be drawn:

1) The available data from the literature shows that only a very small fraction of UHVFA concrete mixes can gain compressive strength over 40 MPa at 28 days, with normal curing conditions and without chemical activation.
2) By lowering the water/binder ratio to 0.2 and properly combining raw materials, even when 80% of the cement is replaced by fly ash, a type of UHVFA concrete with adequate strength and workability for structural use was developed. The compressive strength of both mortar and concrete can reach over 40 MPa at 7-day age, and over 60 MPa at 28-day age.
3) With the water/binder ratio fixed at 0.2, the present study demonstrates that the fly ash replacement ratio has no obvious effect on the cementing efficiency of fly ash, if no more than 80% of cement is replaced by fly ash. However, when the fly ash content is further increased, the cementing efficiency of the fly ash decreases significantly.
4) This study demonstrates that adding a small amount of silica fume can improve the mechanical properties and the sorptivity performance.
5) The replacement of a high percentage of cement with fly ash can significantly reduce the environmental impact and the material cost. Compared to commercial Grade 45 concrete, the developed green concrete shows a reduction of around 70% in CO_2 emission, a reduction of more than 60% in embodied energy, and a reduction of about 15% in material cost.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.conbuildmat.2017.04.188.

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